AQ

PCT

WORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 6 : H01S 3/108, G02F 1/39

A1

(11) International Publication Number: WO 98/01927

(43) International Publication Date: 15 January 1998 (15.01.98)

(21) International Application Number: PCT/GB97/01790

(22) International Filing Date: 3 July 1997 (03.07.97)

(30) Priority Data: 9614006.6 4 July 1996 (04.07.96) GB

(71) Applicant *(for all designated States except US)*: THE SECRETARY OF STATE FOR DEFENCE [GB/GB]; Defence Evaluation and Research Agency, Ively Road, Farnborough, Hampshire GU14 0LX (GB).

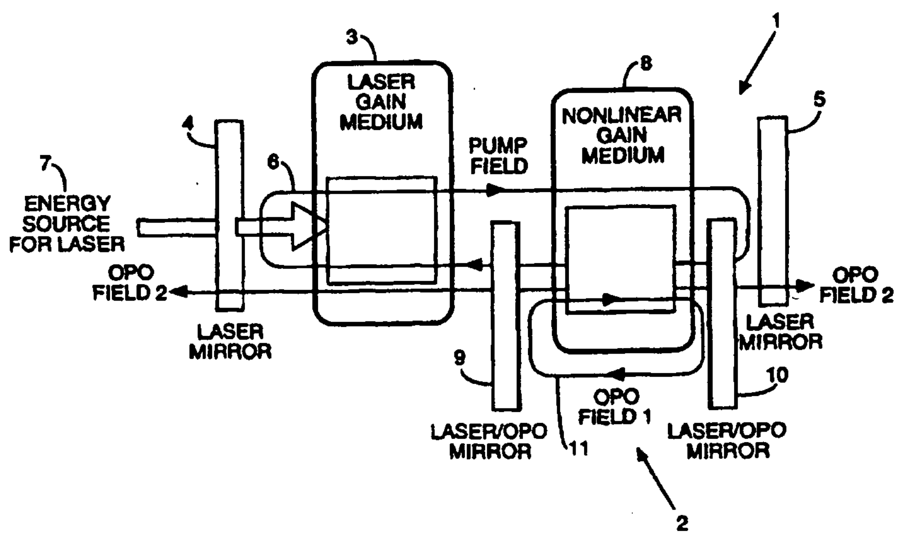
(72) Inventors; and
(75) Inventors/Applicants *(for US only)*: COLVILLE, Finlay [GB/GB]; School of Physics & Astronomy, JF Allen Research Laboratories, St. Andrews University, North Haugh, St. Andrews, Fife KY16 9SS (GB). DUNN, Malcolm, Harry [GB/GB]; School of Physics & Astronomy, JF Allen Research Laboratories, St. Andrews University, North Haugh, St. Andrews, Fife KY16 9SS (GB). EBRAHIMZADEH, Majid [GB/GB]; School of Physics & Astronomy, JF Allen Research Laboratories, St. Andrews University, North Haugh, St. Andrews, Fife KY16 9SS (GB).

(74) Agent: SKELTON, Stephen, Richard; D/IPR (DERA) Formalities, Poplar 2 a, MOD (PE) Abbey Wood #19, P.O. Box 702, Bristol BS12 7DU (GB).

(81) Designated States: GB, JP, US, European patent (AT, BE, CH, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).

Published
With international search report.

(54) Title: OPTICAL PARAMETRIC OSCILLATOR



(57) Abstract

An optical parametric oscillator system comprises a continuous wave, singly resonant optical parametric oscillator (OPO) arranged within the cavity of a laser used to generate the pump wave. The pump laser may have a widely tuneable laser gain medium which enables the OPO to be tuned through the tuning of its pump wave. The pump laser may generate a multiaxial mode pump wave which pumps a non-linear crystal in the OPO to generate two down converted waves; one of the generated waves is resonated in the cavity of the OPO whilst the other generated wave is prevented from resonating by being coupled out of the OPO cavity to form an output signal. A mirror arrangement common to both pump laser and OPO may be used to focus and to ensure co-axiality and co-linearity of pump and resonated waves within the non-linear material; this enhances the setting up and optimisation of the intracavity OPO. Additionally, means may be provided to efficiently couple out a fraction of the resonated wave as a useful output. This resonated output may be single frequency even in the presence of a multimode pump waved. Further, means may be provided to allow the frequencies of the two down converted waves to be independently tuned.

FOR THE PURPOSES OF INFORMATION ONLY

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AL	Albania
AM	Armenia
AT	Austria
AU	Australia
AZ	Azerbaijan
BA	Bosnia and Herzegovina
BB	Barbados
BE	Belgium
BF	Burkina Faso
BG	Bulgaria
BJ	Benin
BR	Brazil
BY	Belarus
CA	Canada
CF	Central African Republic
CG	Congo
CH	Switzerland
CI	Côte d'Ivoire
CM	Cameroon
CN	China
CU	Cuba
CZ	Czech Republic
DE	Germany
DK	Denmark
EE	Estonia
ES	Spain
FI	Finland
FR	France
GA	Gabon
GB	United Kingdom
GE	Georgia
GH	Ghana
GN	Guinea
GR	Greece
HU	Hungary
IE	Ireland
IL	Israel
IS	Iceland
IT	Italy
JP	Japan
KE	Kenya
KG	Kyrgyzstan
KP	Democratic People's Republic of Korea
KR	Republic of Korea
KZ	Kazakstan
LC	Saint Lucia
LI	Liechtenstein
LK	Sri Lanka
LR	Liberia
LS	Lesotho
LT	Lithuania
LU	Luxembourg
LV	Latvia
MC	Monaco
MD	Republic of Moldova
MG	Madagascar
MK	The former Yugoslav Republic of Macedonia
ML	Mali
MN	Mongolia
MR	Mauritania
MW	Malawi
MX	Mexico
NE	Niger
NL	Netherlands
NO	Norway
NZ	New Zealand
PL	Poland
PT	Portugal
RO	Romania
RU	Russian Federation
SD	Sudan
SE	Sweden
SG	Singapore
SI	Slovenia
SK	Slovakia
SN	Senegal
SZ	Swaziland
TD	Chad
TG	Togo
TJ	Tajikistan
TM	Turkmenistan
TR	Turkey
TT	Trinidad and Tobago
UA	Ukraine
UG	Uganda
US	United States of America
UZ	Uzbekistan
VN	Viet Nam
YU	Yugoslavia
ZW	Zimbabwe

OPTICAL PARAMETRIC OSCILLATOR

This invention relates to optical parametric oscillators (OPO) in which a non linear material is optically pumped with light energy to produce optical outputs of different wavelengths to that of the pump energy.

Such oscillators may be pumped by a pump laser (wavelength λ_p, frequency ω_p) to emit light at two wavelengths, termed a signal wave λ_s (frequency ω_s) and an idler-wave λ_i (frequency ω_i) such that $\omega_p = \omega_s + \omega_i$. By convention the signal wave is defined as that wave with the higher frequency of the two generated waves. When the OPO is operated as a double resonant oscillator both the generated signal-wave and idler-wave are resonated. When the OPO is operated as a singly resonant oscillator either the generated signal-wave or the idler-wave is resonated, but not both. Both continuous wave and pulsed pump lasers have been used to provide doubly resonant parametric oscillation. However, the doubly resonant character of the resonator causes the output to be unstable both in amplitude and frequency. Singly resonant parametric oscillation has been achieved using both pulsed, and more recently continuous wave, pump lasers but the threshold pump power for the singly resonant case is much higher (as much as about two orders of magnitude) than the that of the doubly resonant case. Singly resonant oscillators produce a much more stable output and impose less stringent demands on the mirror coating design. For these reasons the singly resonant configurations is the one most frequently used.

In order to provide sufficient energy with a continuous wave beam to exceed threshold, doubly resonant optical parametric oscillators have been placed within the cavity of the laser used to generate the pump wave. In this prior art, such doubly-resonant OPO devices were proposed [see for example Kingston, Proc. IRE, 50, 472 (1962)], analysed theoretically [Oshman & Harris, I.E.E.E. J. Quant. Elec., QE4, 491-502 (1968)] and experimentally demonstrated [Smith & Parker, J. Appl. Phys. 41, 3401-8 (1970)]. Such arrangements suffer from tuning disadvantages.

In the prior art pulsed optical parametric oscillators have been proposed [Kroll, Phys. Rev. 127, 1207-11 (1962)], analysed theoretically [Falk, Yarborough & Ammann, I.E.E.E. J. Quant. Elec. QE7, 359-69 (1971)] and demonstrated [see Lavi, Englander & Lallonz, Op. Lett. 21, 800-2 (1996) and references therein], but the performance characteristics and properties of continuous-wave devices of the present invention are different in kind to those of pulsed devices.

One disadvantage of the prior art is the difficulty of providing sufficient pump energy with a continuous wave pump beam so as to exceed oscillation threshold in a singly-resonant OPO placed external to the pump laser cavity. A second disadvantage of the prior art is the amplitude and frequency instability of a doubly-resonant OPO placed either internal or external to the pump laser cavity, and the difficulty of tuning and aligning the various components to optimise the oscillator output.

In order to avoid the disadvantages associated with the doubly resonant oscillator, while at the same time providing sufficient power with a continuous wave beam to exceed threshold, singly resonant oscillators have been placed within the cavity of the laser used to generate the pump wave. This arrangement is described in United States Patent No 3,628,186, but performance characteristics of embodiments have not been provided.

Such an arrangement as described suffers from a number of problems and disadvantages.

One problem of this prior art is difficulty in aligning the cavities of the singly resonant optical parametric oscillator and the pump laser due to the lack of a means which either partially or fully defines the respective cavity modes with regard to co-linearity concentricity and overlap of beam waists.

According to this invention the aforementioned problem is overcome in relation to continuous wave, singly resonant optical parametric oscillators that are arranged within the cavity of the laser used to generate the pump wave, by a mirror arrangement, or equivalent optical arrangements, that is common to both pump laser and OPO. This arrangement may facilitate the setting up and optimisation of the intracavity OPO, and further may contribute to the stability of the OPO during operation.

A second problem of this prior art is that the resonant wave, either signal or idler, within the optical parametric oscillator is not extracted as useful output. According to the present invention the aforementioned problem is overcome by providing means for extraction of the resonant wave. It is to be noted that even though the pump laser is operating multimode, it is possible for this resonant wave to display the advantage of being single mode (single frequency), with the non-resonant wave being generated in a number of modes corresponding to those of the multimode pump laser. It is therefore advantageous to be able to extract this resonant wave as useful output. A further advantage of being able to extract the resonant wave is that a lower oscillation threshold for the OPO may be obtained by resonating the wave with the lowest loss in the non-linear gain medium, whether it be the signal or the idler wave, while at the same time extracting that wave as useful output.

A third disadvantage of this prior art as stated in USA Patent No. 3,628,186 is that the pump wave power as transmitted by the optical parametric oscillator is not clamped to the threshold power. According to the present invention, means are provided to clamp the pump wave power within the cavity of the pump laser and as transmitted through the optical parametric oscillator to the threshold pump power of that oscillator. This has the advantages of reducing both detrimental thermal effects in the non-linear gain medium as well as the likelihood of optical damage by the pump wave.

A disadvantage of the prior art is that the wavelength of the pump wave is fixed and hence cannot be finely tuned in order to smoothly and continuously tune the wavelength of the non-resonant wave, particularly but not exclusively in those cases where the pump wave is single mode and hence where the non-resonant wave is also single mode (single frequency) given a single frequency resonant wave. An associated disadvantage in the prior art is that the pump wave cannot be coarsely tuned so as to provide extended but coarse (i.e. with mode hops) tuning of the resonant and non-resonant waves without the need to alter the conditions appertaining to phase matching at the non-linear gain medium. According to the present invention the aforementioned problem is overcome by providing means for supplying a pump wave of variable wavelength or frequency to the non-linear gain medium.

A further disadvantage of the prior art is that the wavelengths of the resonated and non-resonated waves (signal and idler waves) cannot be independently chosen, as would be advantageous for example in pump-and-probe spectroscopy or the provision of optical frequency standards with integral ratios between the frequencies of pump, signal and idler waves. According to the present invention the aforementioned problem is overcome by providing means for supplying a pump wave of variable frequency to the non-linear gain medium, as well as for simultaneously altering the phase matching conditions by appropriate adjustment of the non-linear gain medium itself.

The present invention provides an optical parametric oscillator (OPO) in which the non-linear gain medium is placed within the cavity (resonator) of the laser used to pump the optical parametric oscillator and where the optical parametric oscillator is operated both as a singly-resonant oscillator (SRO), in which either the generated signal- or idler-wave is resonated, but not both, and also as a continuous-wave device, with an output formed by either or both generated waves.

According to this invention an optical parametric oscillator (OPO) system comprises:

a continuous wave pump laser having a laser gain medium within a laser cavity formed between reflecting surfaces;

a singly resonant parametric oscillator having a non-linear gain material capable of generating both a signal wave and an idler wave when illuminated by a pump wave, the non linear material being arranged within the pump laser cavity between reflecting surfaces forming an oscillator cavity resonant at one of the generated waves and including means for preventing feedback of the non-resonant wave within the oscillator cavity,

means for focusing both pump and resonated wave to required waist dimensions within the non linear material to give a common coaxial and co-linear optical path to both pump and resonated wave within the non linear material, whereby simultaneous alignment of both pump and oscillator cavities is obtained with matching of said beam waists, and

means for directing one of the generated wavelengths from the oscillator to form an output signal.

Preferably the oscillator and pump laser cavities are arranged with at least one common reflecting surface which focuses both pump and resonated waves to required waist dimensions within the non linear material to give a common coaxial and co-linear optical path to both pump and resonated waves within the non linear material, whereby simultaneous alignment of both pump and oscillator cavities is obtained with matching of said beam waists. For example the non-linear material may be arranged between two focusing mirrors.

Preferably the laser gain material is tuneable so that the phase match bandwidth of the parametric oscillator may be tuned by tuning the wavelength of the pump wave without the need to alter the orientation, temperature or other relevant parameter of the non-linear gain medium itself. The tuning may be achieved by a suitable tuning element within the pump laser cavity. Alternatively, the pump laser may operate at a fixed frequency and the non linear material is tuned by variation of its temperature, angular position within the oscillator cavity, or some other parameter influencing phase matching to vary oscillator frequency.

Preferably both the laser gain material and the non-linear gain material may be simultaneously tunable, so allowing independent selection of idler wave and signal wave frequencies or wavelengths.

The non linear material may be KTP or $LiNbO_3$ or isomorphs of these materials, or periodically poled versions of these materials or their isomorphs, or LBO.

One of the reflecting surfaces forming the oscillator cavity may be partly transmitting at the resonant wave frequency, the transmission being chosen to optimise the output power available from the resonant wave.

The non-linear material may have its temperature and/or angular position varied to vary the ratio of ω_s to ω_i. This may be additional to varying the pump laser frequency by the birefringent tuner element.

Embodiments of the invention will now be described by way of example only. and with reference to the attached figures. in which:

Figure 1 is a schematic view showing the generic principles of the invention:

Figure 2 shows a first embodiment with a parametric oscillator within the cavity of a pump laser sharing common focusing mirrors:

Figure 3 shows the dependence of both the intracavity pump-wave power and the idler-wave output power on the pump power delivered by a priming argon ion laser to the gain medium of the pump laser for the case where the pump-wave wavelength is approximately 800 nm: and where the pump power (intracavity) is clamped by the onset of oscillation in the parametric oscillator;

Figure 4 shows the dependence of the wavelength of the generated signal-wave of the optical parametric oscillator on the wavelength of the pump-wave generated by the pump laser:

Figure 5 shows the signal-wave power generated by the singly-resonant. continuous-wave optical parametric oscillator as a function of time:

Figure 6 shows the spectral content of the generated resonant-wave (signal wave in this case) as monitored by a scanning interferometer. indicating single-axial- mode (single-frequency) oscillation of the optical parametric oscillator:

Figure 7 is a schematic view showing a second embodiment of the invention in which the cavity of the pump laser is a ring (travelling wave) resonator:

Figure 8 is a schematic view showing a third embodiment of the invention in which both the cavity of the pump laser and also the cavity of the optical parametric oscillator are ring (travelling wave) resonators:

Figure 9 is a schematic view showing a fourth embodiment of the invention in which the gain medium of the pump laser is not tuneable and wide-tuning of the optical parametric oscillator is achieved by variation of one of the parameters of its non-linear gain medium;

Figure 10 shows multi parameter tuning of the singly resonant oscillator; and

Figure 11 shows the power output for the resonated and non-resonated waves.

Figure 1 shows the principles of the optical parametric oscillator. It comprising a pump laser 1 containing a parametric oscillator 2. The pump laser 1 itself comprises a laser gain medium 3 located between two mirrors 4, 5 which define a pump laser cavity 6. The laser gain medium receives input power 7, e.g. from a priming laser or other power source (not shown). The parametric oscillator 2 comprises a non-linear gain medium 8 located between two mirrors 9, 10 which form an oscillator cavity 11. Upon receipt of input energy 7 the laser gain medium 3 is stimulated to emit light between the two mirrors 4, 5 and in doing so passes this light through the non-linear gain medium 8 causing it to emit additional light one component of which resonates between the two oscillator mirrors 9, 10. The oscillator cavity 11 resonates at either a signal-wave or idler-wave (OPO field 1). The non resonated wave (OPO field 2) exits through either one or both of mirrors 9, 10. In addition useful output of OPO field 1 may be obtained by making either mirror 9 or 10 partially transmitting for this wavelength.

In one embodiment of the invention mirrors 5 and 10 are the same (common) mirror. In another embodiment of the invention the laser gain medium 3 is tunable, so enabling the wavelength of the pump wave or field to be tuned. In another embodiment of the invention the phase-matching condition in the non-linear gain medium may be independently altered, which together with the ability to tune pump field allows the signal and idler waves to be independently tuned. In a further embodiment of the invention, the resonated wave (OPO field 1) is efficiently coupled out of the oscillator cavity 11 by selecting the appropriate transmission for either mirror 9 or 10.

One specific embodiment of an OPO system is shown in Figure 2 and follows the principles shown in Figure 1. The system comprises a pump laser , a parametric oscillator, and a power source.

The pump laser comprises a crystal of Ti:sapphire 3, forming a laser gain medium, located within a standing-wave cavity 6 formed by mirrors M1-6. The crystal is a standard c-cut crystal with Brewster-angled faces, and is 7.5mm long. Mirrors M2, M3 are focusing mirrors of radius of curvature 10cm, that focus the pump-wave mode to a suitable beam waist, typically about 20μm, within the crystal 3. Mirrors M1, and M4 are highly reflecting plane mirrors. Mirror M6 and M5 have a radius of curvature of 20cm and focus the pump beam to a waist of typically 30 to 50μm. A tuning element is formed by birefringent plate 15 which allows tuning of the pump laser linewidth and centre frequency by rotation of the plate 15. The pump beam within the cavity 6 is polarised with its electric vector in the plane of the figure 2.

The OPO comprises a non-linear gain medium 8 which is a potassium titanyl phosphate (KTP) crystal located within the pump laser cavity 6 and between mirror M5. M6 with the waist of the pump beam in the centre of the crystal 8. The KTP crystal 8 is 20cm long and is cut for standard type II noncritical phase matching in which the pump wave and generated signal wave are polarised with their electric vectors in the plane of the figure. and the generated idler wave is polarised with its electric vector normal to the plane of the figure. The optical faces (y-z faces. 4x4mm) of the KTP crystal 8 are cut for normal incidence of the various waves when they propagate along the x-axis of the crystal 8. and are antireflection coated; e.g. residual reflectivity's typically <0.5% for pump wave and resonated signal wave. and <5% for the non resonated idler wave.

The signal-wave is resonated within the KTP crystal 8 by means of the standing-wave cavity formed by mirrors, M6. M5. a beamsplitter 16 (which is highly reflecting for the signal wave >99% and high transmitting for the pump wave > 99%). and mirror M7. All these mirrors are of high reflectivity for the signal-wave (>99%). Additionally Mirror M7 is significantly reflective at the pump wavelength. A signal wave output ω_s may be taken from transmission through M7.

The idler-wave ω_i, which is not resonated in this singly-resonant oscillator but which is generated as a single-pass wave in both directions through the KTP crystal 8, leaves the cavity 11 through either / both mirror M6 or/and mirror M5, both of which have a significant transmission (>60%) at the idler-wave wavelength. The idler-wave may be used as an output, but will not have a single frequency if the pump laser operates at multiple frequencies.

The input power source 7 comprises an argon-ion laser 17 whose output is directed via mirrors 18, 19, 20, 21, a wave plate 22, and focusing lens 23 and mirror M2 into the Ti:sapphire crystal 3. Typically the laser 17 has an output at 514.5nm and is focused by lens 23 so as to be mode matched with the pump wave mode inside the crystal 3.. and being in a suitable polarisation state (electric vector orthogonal to the plane of the figure), which can be controlled using the wave plate 22 so as to optimise the gain experienced by the pump wave within the crystal 3.

In operation the Argon ion laser 17 optically pumps the crystal 3 to cause generation of a pump beam. The pump wave can be multimode (multi axial mode, i.e. multi frequency) while still efficiently pumping a single axial mode signal wave in the OPO. In one example the pump wave had a linewidth of the order of 20GHz. As noted above, mirrors M5, M6 focus the pump wave to a beam waist (i.e. required energy density) within the KTP crystal 8; additionally they focus the signal wave to a beam waist to mode match with the pump wave.

An advantage of the use of common mirrors M6 and M5. is that when the optical cavity 6 of the pump-wave has been aligned and the pump laser 1 thereby brought into oscillation, it is then no longer necessary or appropriate to readjust these two mirrors in seeking to bring the cavity 11 of the OPO into resonance and hence the OPO into oscillation, these latter being effected solely through alignment of mirror M7. Further, by making the beamsplitter 16 to be slightly reflecting (~0.5%) at the pump-wave wavelength and with mirror M7 significantly reflecting at the pump-wave wavelength, then the correct alignment of the OPO cavity, effected through the adjustment of mirror M7, can be gauged through the enhancement in the pump-wave that occurs simultaneously with this alignment, this enhancement being as a result of the increased feedback occasioned through mirror M7 and the beamsplitter 16 reflecting back pump-wave into the pump laser cavity.

The power output characteristics of the system of Figure 2 are shown in Figure 3 in which the pump-wave (intracavity) power and the idler-wave power are displayed as a function of the optical power applied to the Ti:sapphire crystal 3 by the argon laser 17. As expected, the intracavity pump-wave power clamps at the threshold value for oscillation of the OPO.

Figure 4 shows the tuning range of the signal-wave of the OPO as a function of the pump-wave wavelength which is scanned across the gain profile of the Ti:sapphire by altering the birefringent tuner 15.

Figure 5 shows the temporal behaviour of the signal wave as a function of time, the stability of which is consistent with the OPO oscillating with only one resonant down-converted wave (i.e. singly-resonant).

Figure 6 is the signal-wave output (resonated wave) from the OPO as monitored by a scanning interferometer, and shows the single-axial-mode (single-frequency) nature of this output despite the pump-wave being highly multi-axial-mode.

A second embodiment of the invention is shown in Figure 7 in which the cavity 6 of the pump laser is now a travelling wave cavity between mirrors 30-33 with the pump-wave constrained to be unidirectional, by the incorporation into the cavity of a suitable unidirectional device (not shown but may be e.g. a Faraday rotator and birefringent plate), but with all other features the same as in embodiment 1 above. This embodiment ensures single-axial-mode (single-frequency) oscillation of the pump laser because of the avoidance of spatial hole-burning in the Ti:sapphire gain medium 3, although possibly requiring the incorporation into the pump laser cavity 6 of additional line narrowing elements, not explicitly shown, in order to ensure that such single frequency oscillation is maintained. The advantage of this embodiment is that the optical parametric oscillator is now pumped by a single-frequency pump-wave, so that the non-resonated idler output (though mirror 33) is also single-frequency provided that the resonated signal wave (output through mirror 9) is or is constrained to be single frequency. However a disadvantage of this arrangement is that the parametric gain in the non-linear crystal 8 is now unidirectional because of the unidirectional nature of the pump-wave.

A third embodiment of the invention is shown in Figure 8 in which the cavity 11 of the optical parametric oscillator is now also a travelling wave (ring) cavity between mirror 34-37, but with all other features the same as in Figure 7 above. The advantage of this embodiment is a reduction in the parasitic loss associated with the down-converted resonated wave in the cavity of the optical parametric oscillator compared to the case where this is a standing wave cavity with only unidirectional gain, as in Figure 7 above.

In a specific example of such an OPO. the travelling-wave Ti:sapphire laser pumps an 11.5mm long crystal of KTA as the nonlinear material. Single frequency operation of the Ti:sapphire laser is obtained. with single frequency outputs for both signal and idler waves simultaneously.

A fourth embodiment of the invention is shown in Figure 9 and which differs from the Figure 2 embodiment in that the gain medium 3 of the pump laser is now no longer widely tuneable. In this embodiment it is now no longer possible to tune to any significant extent the optical parametric oscillator 2 through tuning the pump-wave wavelength, and this tuning must now be effected by altering some parameter of the non-linear gain medium 8 itself. such as the temperature of the crystal or the angle of propagation of the radiation through the crystal. For such an embodiment the non linear crystal may be a periodically poled lithium niobate ($LiNbO_3$) crystal.

A fifth embodiment of the invention is where the gain medium of the pump laser 3 in Figure 2 is tuneable, but means for wavelength tuning of the output signal and idler beams from the OPO are also available through temperature-tuning of the non-linear material 8 or grating-tuning in the case where the non-linear material is periodically-poled. such as LiNbO3 (PPLN). One significant advantage of this scheme is that it provides a multi-parameter tuning capability and allows access to a particular combination of pump, signal. and idler frequencies through independent control of pump wavelength. temperature of the non-linear material. or the period of the quasi-phase-matching grating.

In a specific example of such an OPO, the non-linear gain medium 8 is a 19-mm-long crystal of PPLN incorporating eight gratings ranging in period from 21 to 22.4 μm, and is pumped at the intracavity focus of a tuneable Ti: sapphire laser; the laser gain medium 3 is a Ti: sapphire crystal as described in embodiment 1. By using a combination of pump-wavelength-tuning and grating-tuning at a fixed crystal temperature of 165°C, a signal (idler) wavelength range of 1.070-1.28 μm (2.30-3.33 μm) has been accessed, as shown in Figure 10. Additional means for tuning is also available by changing the temperature of the PPLN crystal.

A sixth embodiment of the invention is where one of the OPO mirrors, for example M7 in Figure 2, is partially transmitting for the resonated field 1. This scheme allows the useful extraction of a narrow-linewidth, single-longitudinal-mode resonated beam even when the pump laser itself has broadband, multi-longitudinal-mode characteristics.

In a specific example of such an OPO, a multi-longitudinal-mode, standing-wave Ti: sapphire laser pumps an 11.5-mm-long crystal of KTA as the non-linear material to provide tunable outputs over 1. 1 1- 1.22 μm (signal) and 2.38-2.92 μm (idler) through pump-tuning. By employing a partially transmitting OPO mirror (M7 in figure 2) with a transmission of 1.2% for the resonated (signal) beam, useful output powers in excess of 500 mW in a narrow linewidth signal field have been coupled out of the resonator across most of the tuning range, as shown in Figure 11(a). The output power simultaneously extracted in the non-resonant multimode (idler) beam is also greater than 500 mW over this range, as shown in Figure 11 (b).

A seventh embodiment of the invention is where the tuneable laser gain medium 3 in Figure 2 is a crystal of Ti:sapphire and the power source 17 is a diode-laser-pumped, all-solid-state green laser.

In one specific design of such an OPO, a commercial diode-laser-pumped frequency-doubled Nd:YVO_4 laser at 532 nm (Spectra-Physics, *Millennia)* is the power source for a tuneable Ti:sapphire laser pump source. By constructing an intracavity SRO using a 19-mm-long crystal of PPLN placed at the intracavity focus of the Ti:sapphire laser, signal (idler) wavelengths in the range 1.070-1.28 μm (2.30-3.33 μm) have been generated (Figure 10), and an output power of 100 mW has been produced in the non-resonant idler beam with 5.5 W of input power from the Millennia laser.

An eighth embodiment of the invention is where the laser gain medium 3 is a crystal of Nd: YAG, Nd: YLF, or Nd: YVO_4, the power source 17 is a semiconductor diode laser, and the non linear material 8 is KTA, PPLN, or other periodically-poled materials including PP-KTP, PP-RTA, PP-KTA, PP-RTP and PP-CTA.

In one specific design of such an OPO, the energy source is an AlGaAs semiconductor laser operating near 800 nm, the laser gain medium is a crystal of ND:YLF providing pumping radiation at 1.047 μm, and the non-linear gain material is a 15-mm crystal of KTA. This device can provide fixed-wavelength signal (idler) radiation at 1.505 (3.440) gm, with a total output power of up to 250 mW for 7 W of input power from the semiconductor diode laser to the ND:YLF crystals.

A ninth embodiment of the invention is where the tuneable laser gain medium 3 is a vibronic crystal other than Ti:sapphire, for example Cr:LiSAF, Cr:LiCAF, Cr:LiSGaF, or Cr:forsterite, and the energy source 17 is a semiconductor diode laser.

CLAIMS

1. An optical parametric oscillator (OPO) system comprising:

a continuous wave pump laser (1) having a laser gain medium (3) within a laser cavity (6) formed between reflecting surfaces (M1 to M6);

a continuous wave, singly resonant parametric oscillator (2) having a non-linear gain material (8) capable of generating both a signal wave and an idler wave when illuminated by a pump wave, the non linear material (8) being arranged within the pump laser cavity (6) between reflecting surfaces (M5, M6) forming an oscillator cavity (11) resonant at one of the generated waves and including means (M5) for preventing feedback of the non-resonant wave.

means (M5, M6) for focusing both pump and resonated wave to required waist dimensions within the non linear material (8) to give a common coaxial and co-linear optical path to both pump and resonated wave within the non linear material (8), whereby simultaneous alignment of both pump and oscillator cavities is obtained with matching of said beam waists, and

means (M5, M7, 16) for directing one of the generated wavelengths from the oscillator to form an output signal.

2. The system of claim 1 wherein the pump and oscillator cavities are arranged with at least one common reflecting surface which focuses alone or with additional optical elements both pump and resonated wave to required waist dimensions within the non linear material to give a common coaxial and co-linear optical path to both pump and resonated wave within the non linear material.

3. The system of claim 1 wherein the pump laser is tuneable in frequency.

4. The system of claim 1 wherein the laser gain medium is selected from: Cr:LiSAF, Cr:LiCAF, Cr:LiSGaF, Cr:forsterite, Cr:YAG.

5. The system of claim 2 wherein the pump laser is tuned by a birefringent element.

6. The system of claim 1 wherein the non-linear material is tunable so that the signal and idler waves may be tuned.

7. The system of claim 1 wherein the non linear material is tuneable by variation of its temperature, angular position within the cavity, or grating period.

8. The system of claim 1 wherein the non linear material is selected from:- KTP, $LiNbO_3$, PPLN, PP-KTP, PP-RTA, PP-KTA, PP-RTP, PP-CTA.

9. The system of claim 1 wherein at least one of the reflecting surfaces (M7) forming the oscillator cavity or any optical component internal to the oscillator cavity is adjustable to contribute to enhancing optimum pump laser intracavity power.

10. The system of claim 1 including means for directing the non-resonant generated wavelength from the system to form the output signal.

11. The system of claim 1 including means for directing the resonant generated wavelength from the system to form the output signal.

12. The system of claim 1 including means for directing the non-resonant and resonant generated wavelengths from the system to form separate output signals.

13. The system of claim 1 wherein the pump laser is a multi-axial mode laser and the resonated generated wave output is a single-axial-mode output

14. The system of claim 1 wherein the pump wave is clamped to the threshold of the parametric oscillator.

15. The system of claim 1 wherein the cavity of the pump laser is a ring (travelling wave) resonator.

15. The system of claim 1 wherein the cavity of the optical parametric oscillator is a ring (travelling wave) resonator.

15. The system of claim 1 wherein the cavities of both the pump laser and optical parametric oscillator are ring (travelling wave) resonators

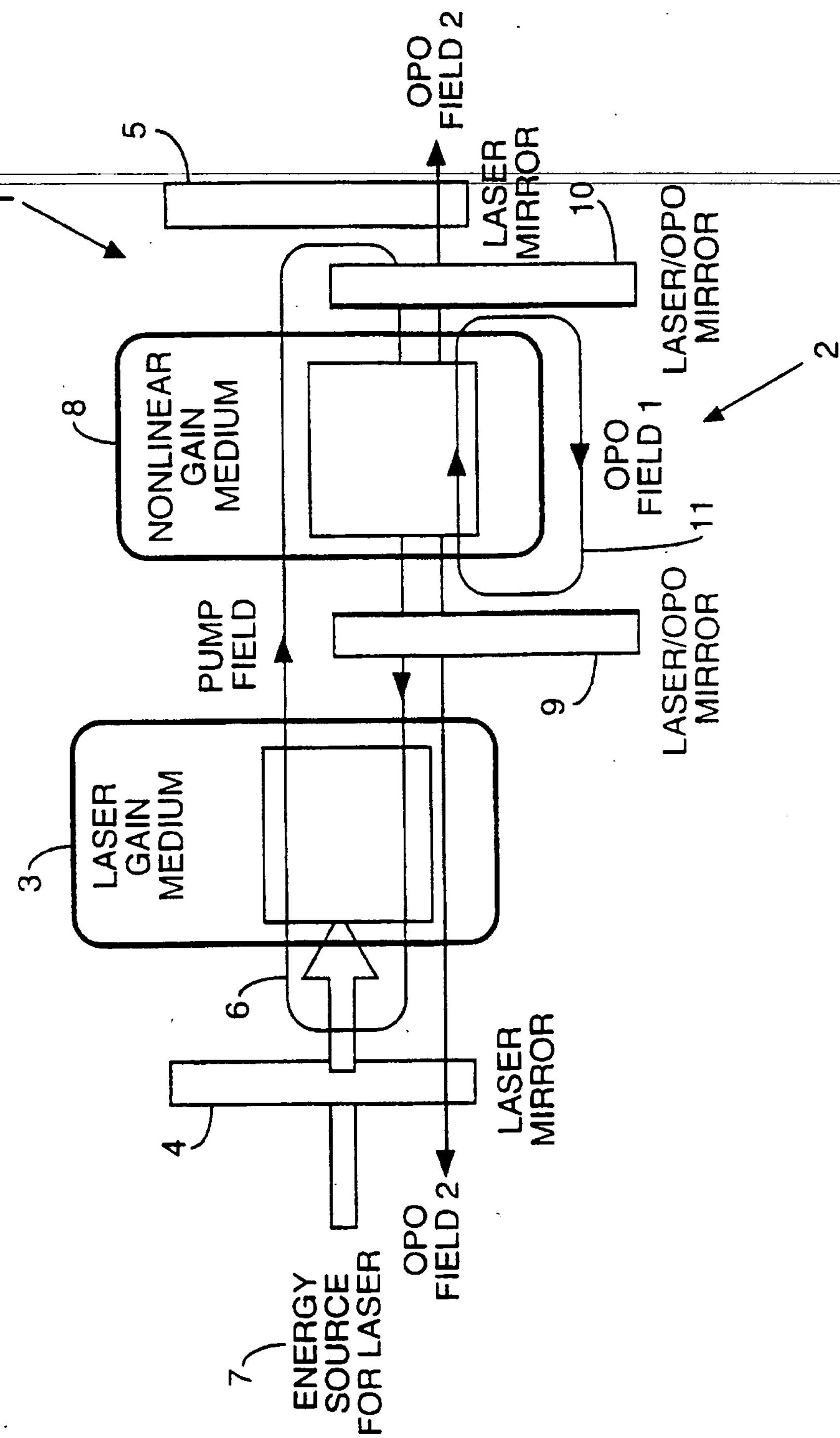

1
2
OPO FIELD 2
5
LASER MIRROR
10
LASER/OPO MIRROR
8
NONLINEAR GAIN MEDIUM
OPO FIELD 1
11
PUMP FIELD
LASER/OPO MIRROR
9
3
LASER GAIN MEDIUM
6
LASER MIRROR
4
OPO FIELD 2
7
ENERGY SOURCE FOR LASER

Fig.1.

Fig.2.

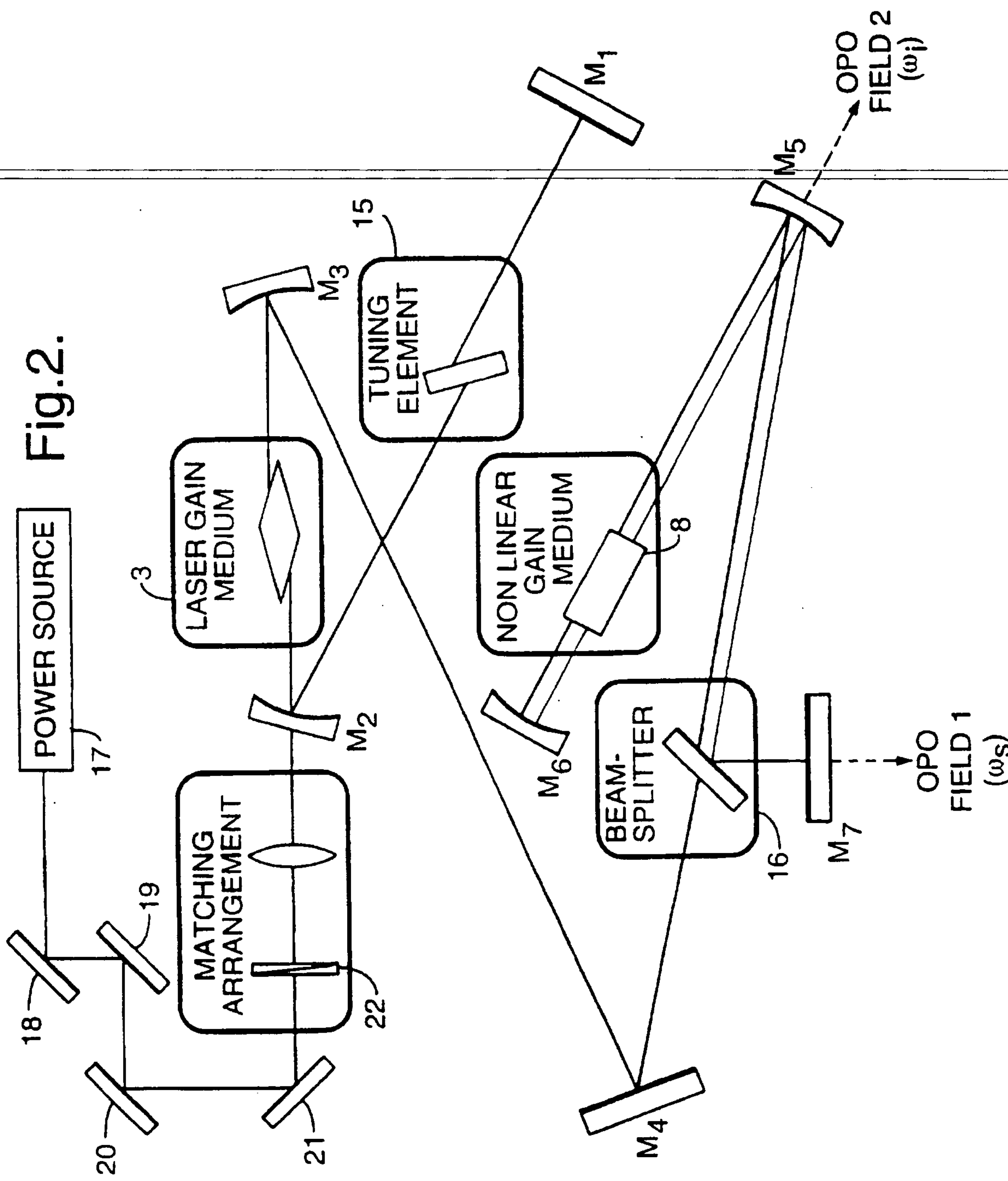

POWER SOURCE
17
18
19
20
21
22
MATCHING ARRANGEMENT
LASER GAIN MEDIUM
3
M_2
M_3
TUNING ELEMENT
15
M_1
M_5
OPO FIELD 2 (ω_i)
NON LINEAR GAIN MEDIUM
8
M_6
BEAM-SPLITTER
16
M_7
OPO FIELD 1 (ω_s)
M_4

Fig.3.

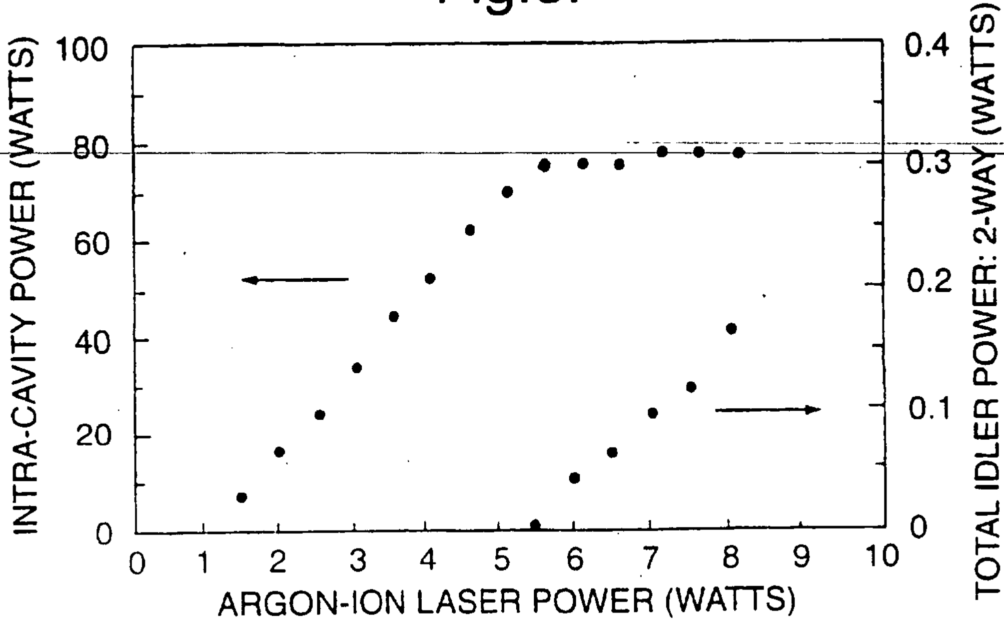

INTRA-CAVITY POWER (WATTS)
100
80
60
40
20
0
0.4
0.3
0.2
0.1
0
TOTAL IDLER POWER: 2-WAY (WATTS)
0 1 2 3 4 5 6 7 8 9 10
ARGON-ION LASER POWER (WATTS)

Fig.4.

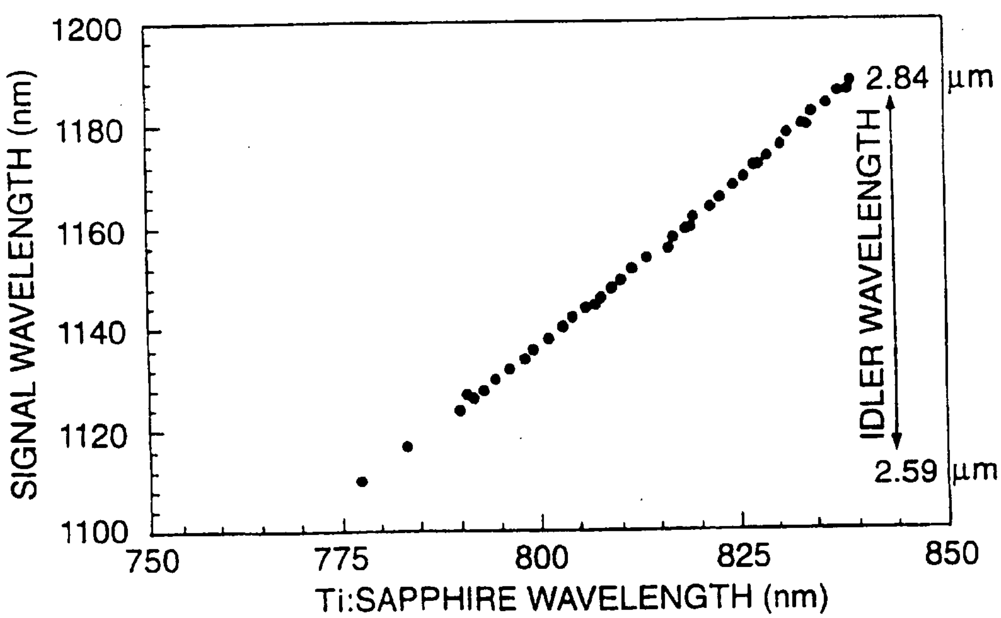

SIGNAL WAVELENGTH (nm)
1200
1180
1160
1140
1120
1100
750 775 800 825 850
Ti:SAPPHIRE WAVELENGTH (nm)
2.84 µm
IDLER WAVELENGTH
2.59 µm

Fig.5.

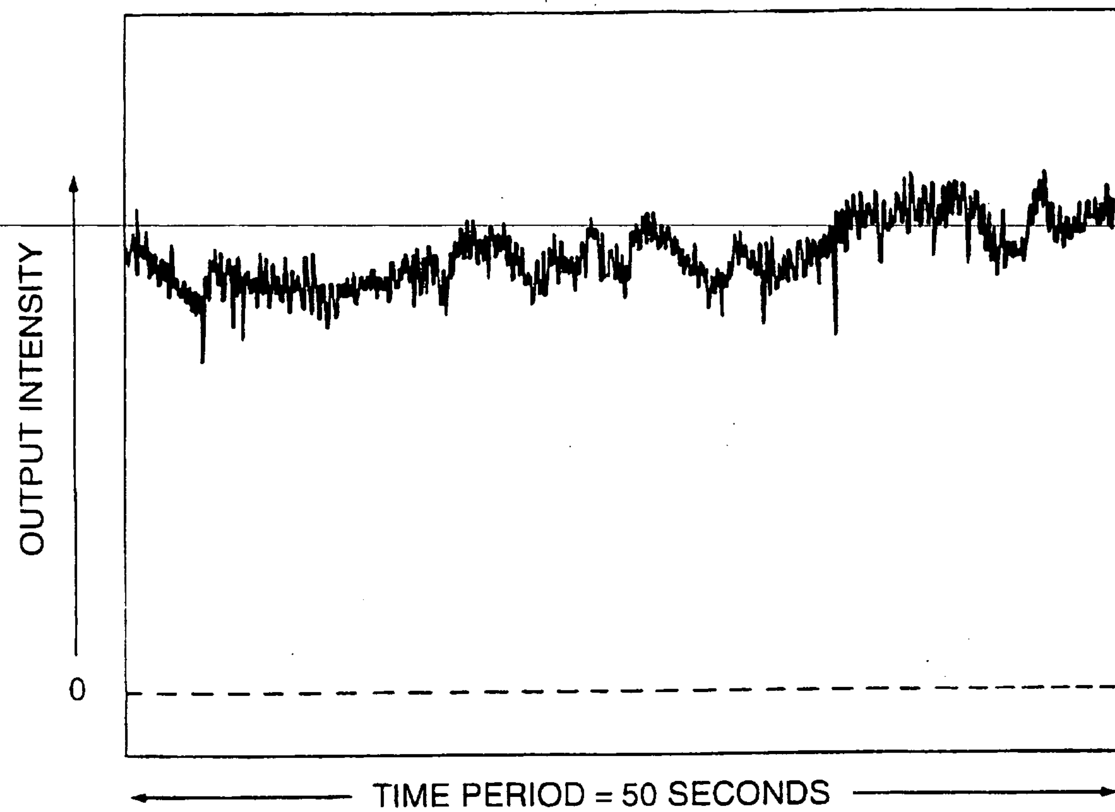

OUTPUT INTENSITY
0
TIME PERIOD = 50 SECONDS

Fig.6.

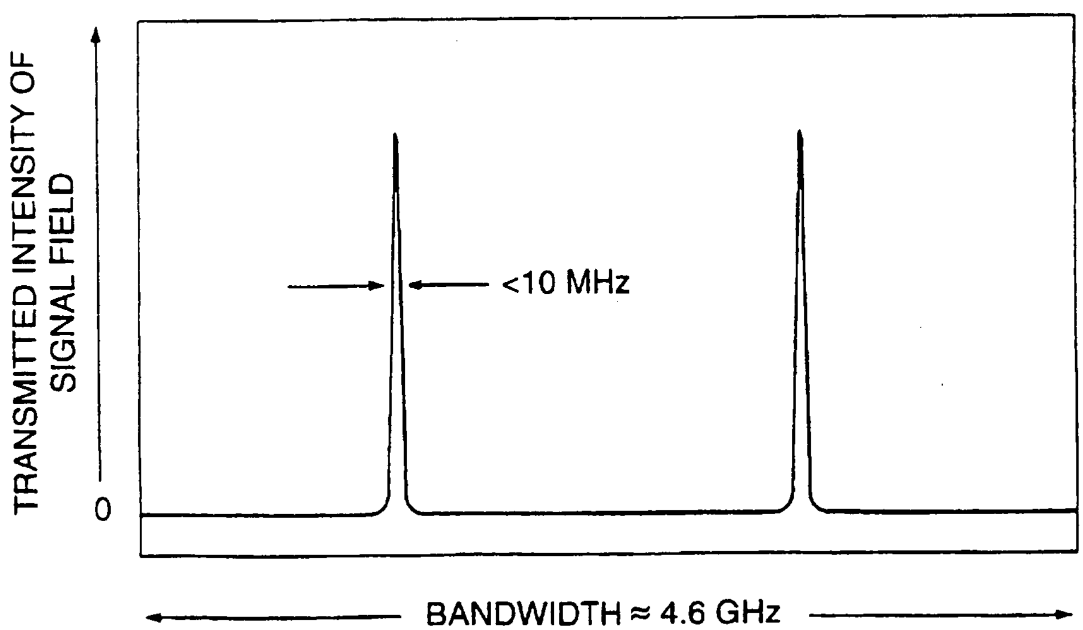

TRANSMITTED INTENSITY OF SIGNAL FIELD
0
<10 MHz
BANDWIDTH ≈ 4.6 GHz

Fig.7.

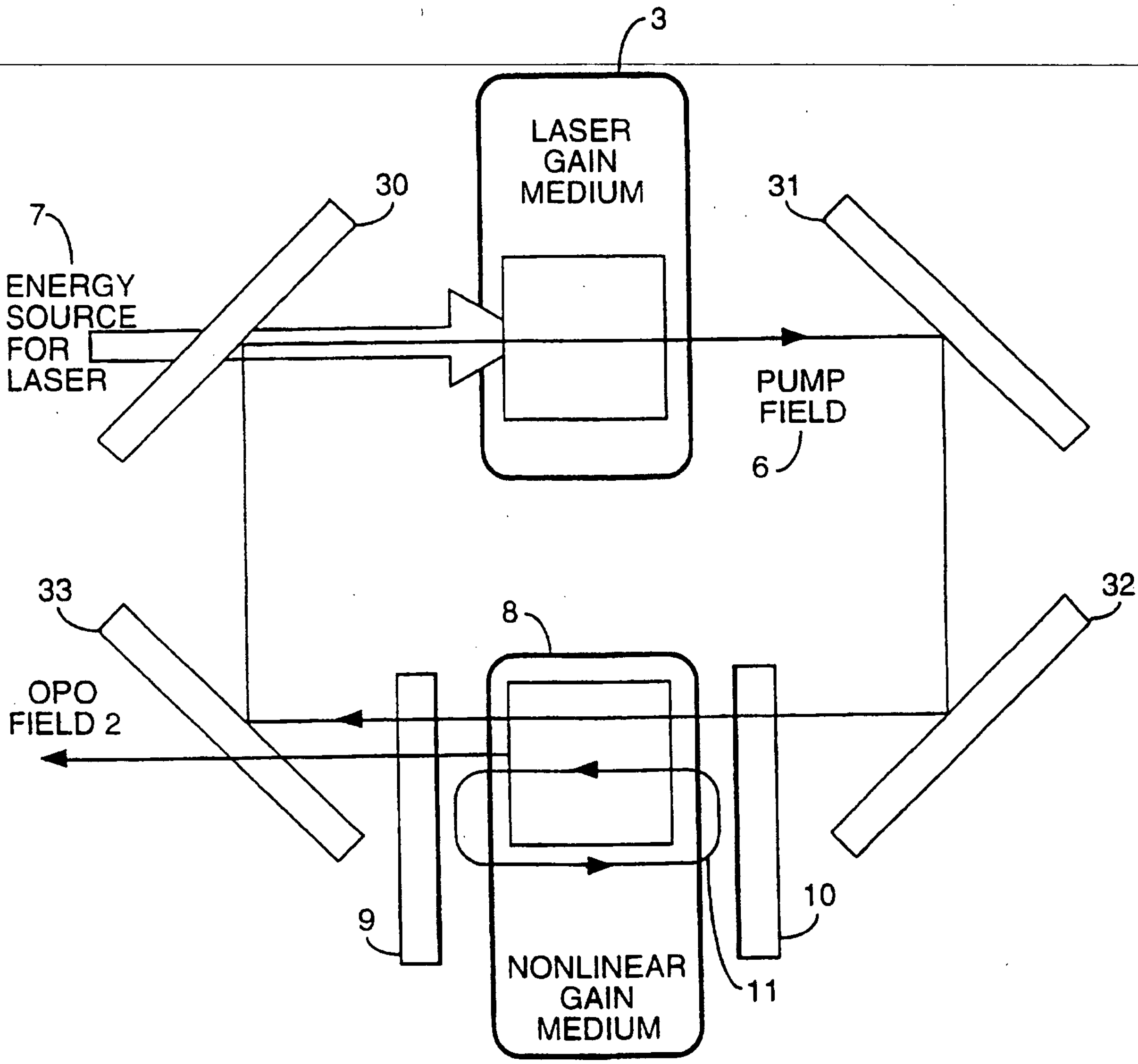
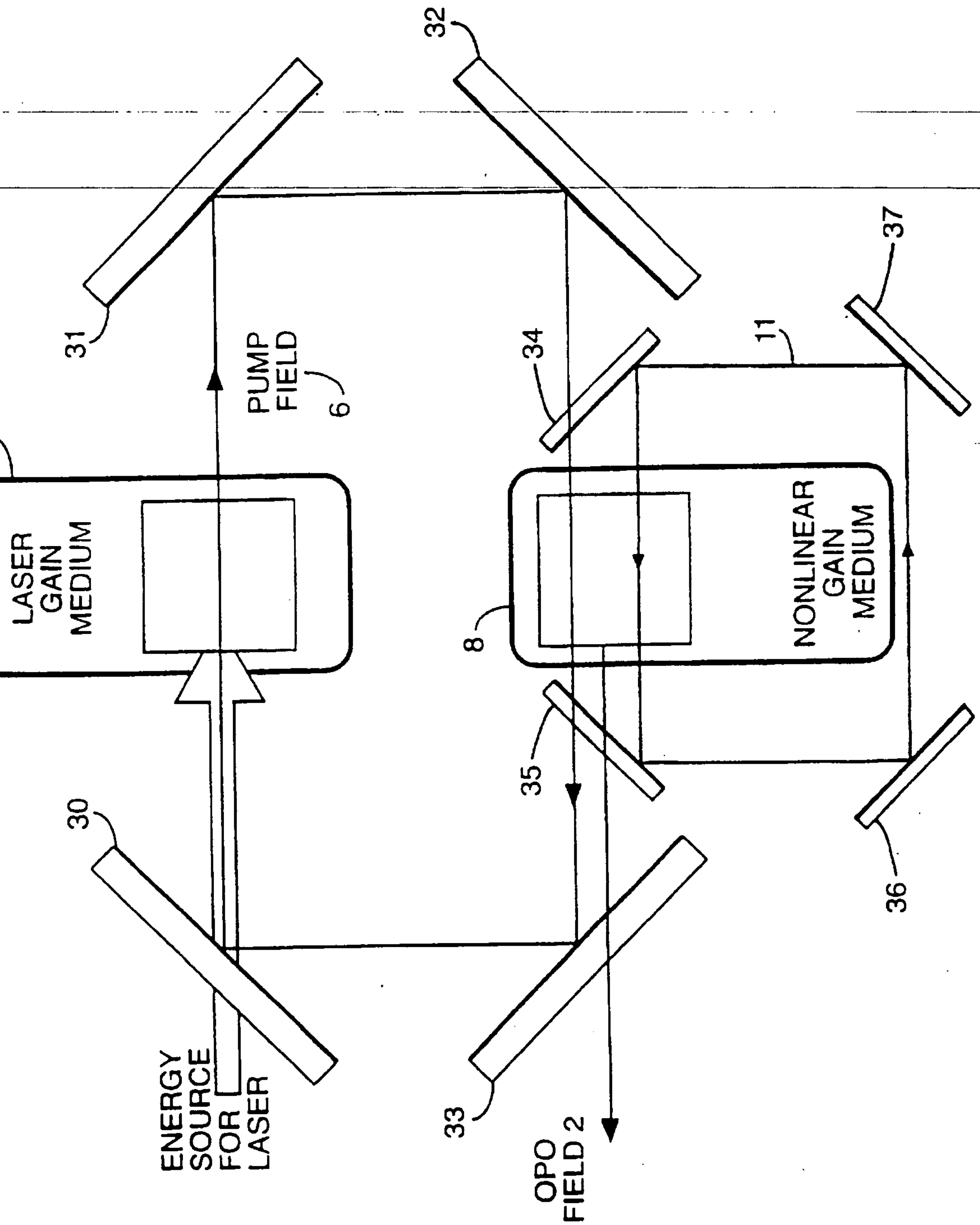

3
LASER
GAIN
MEDIUM
30
31
7
ENERGY
SOURCE
FOR
LASER
PUMP
FIELD
6
33
8
32
OPO
FIELD 2
9
10
11
NONLINEAR
GAIN
MEDIUM

Fig.8.



32
31
37
34
11
PUMP FIELD
6
3
LASER GAIN MEDIUM
NONLINEAR GAIN MEDIUM
8
35
30
36
33
ENERGY SOURCE FOR LASER
OPO FIELD 2

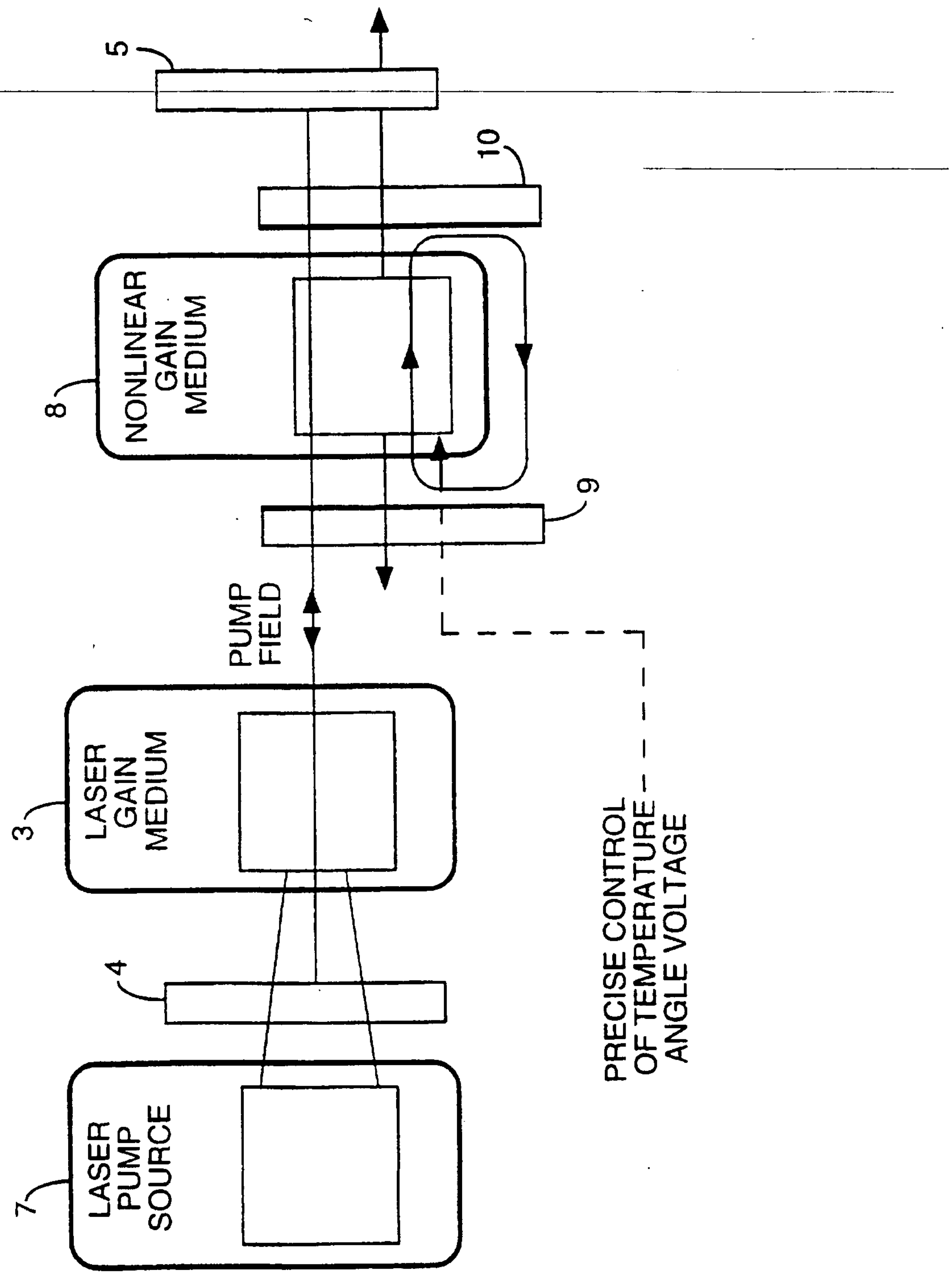

5
10
8
NONLINEAR GAIN MEDIUM
9
PUMP FIELD
3
LASER GAIN MEDIUM
4
7
LASER PUMP SOURCE
PRECISE CONTROL OF TEMPERATURE ANGLE VOLTAGE

Fig.9.

Fig.10.

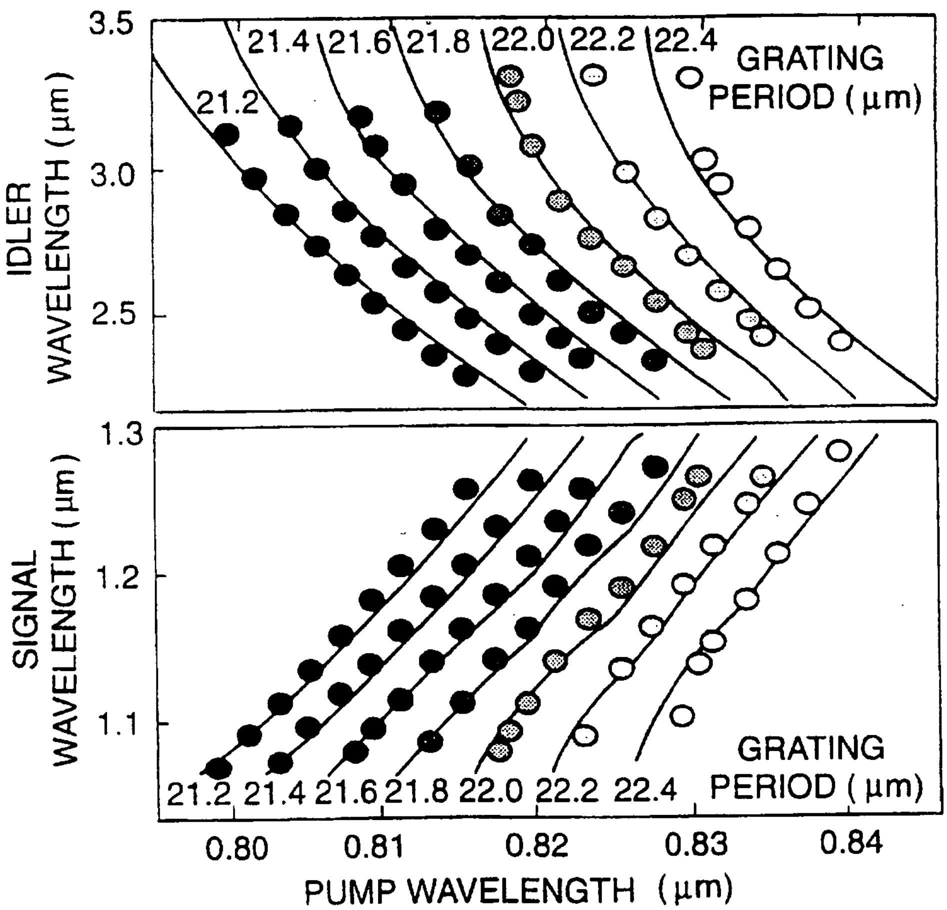
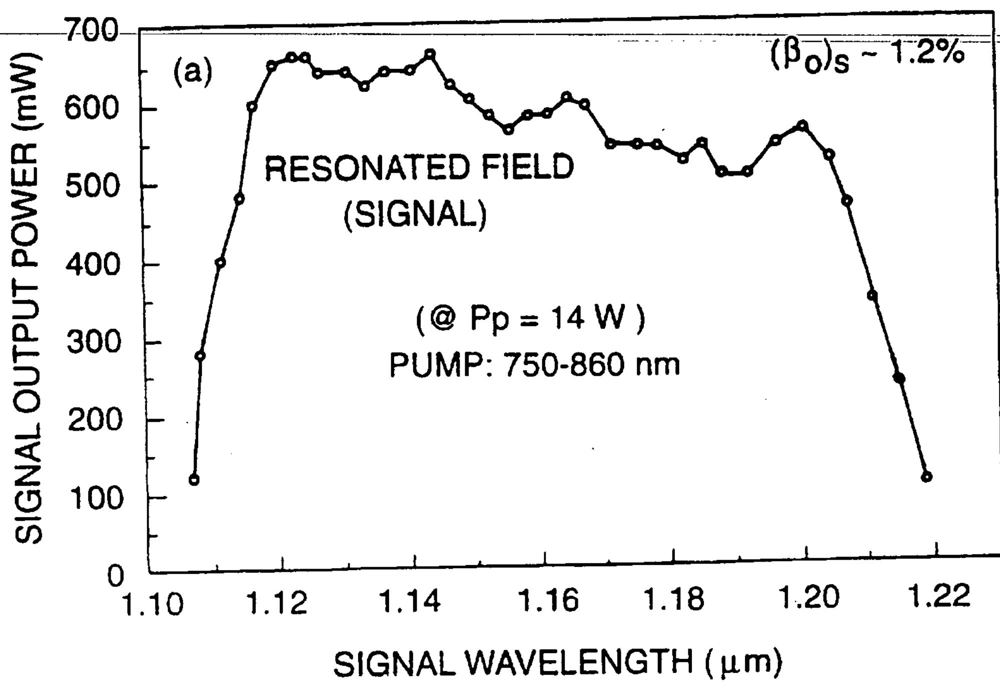
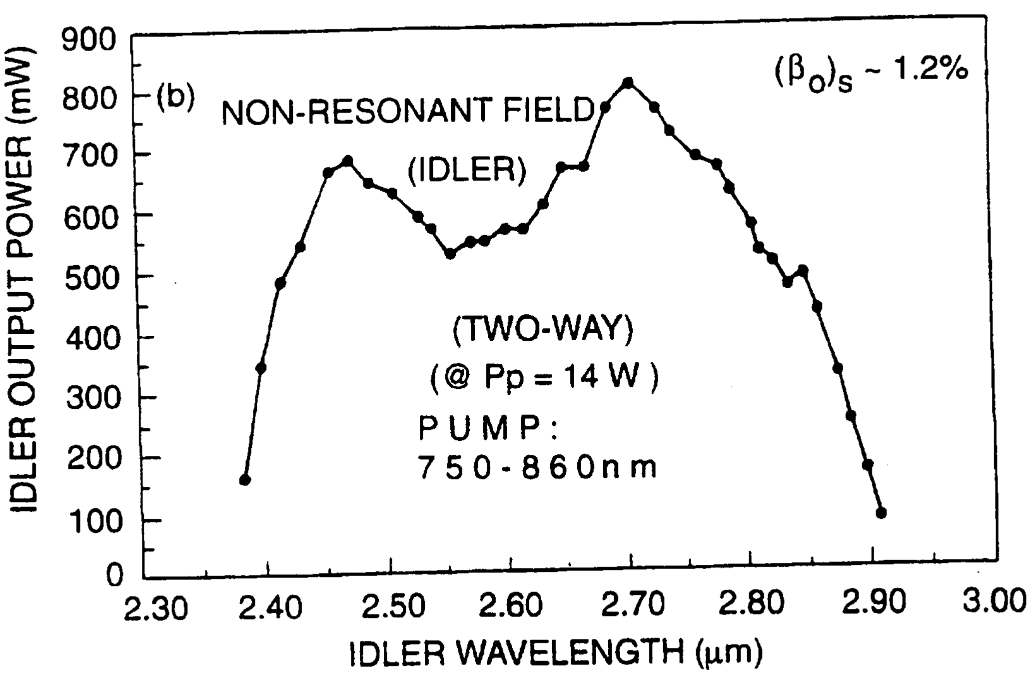

3.5
3.0
2.5
1.3
1.2
1.1
IDLER WAVELENGTH (μm)
SIGNAL WAVELENGTH (μm)
21.2
21.4
21.6
21.8
22.0
22.2
22.4
GRATING PERIOD (μm)
21.2 21.4 21.6 21.8 22.0 22.2 22.4
GRATING PERIOD (μm)
0.80
0.81
0.82
0.83
0.84
PUMP WAVELENGTH (μm)

Fig.11.


(a)
$(\beta_o)_s$ ~ 1.2%
RESONATED FIELD
(SIGNAL)
(@ Pp = 14 W)
PUMP: 750-860 nm
SIGNAL OUTPUT POWER (mW)
SIGNAL WAVELENGTH (μm)
0
100
200
300
400
500
600
700
1.10
1.12
1.14
1.16
1.18
1.20
1.22


(b)
$(\beta_o)_s$ ~ 1.2%
NON-RESONANT FIELD
(IDLER)
(TWO-WAY)
(@ Pp = 14 W)
PUMP:
750-860nm
IDLER OUTPUT POWER (mW)
IDLER WAVELENGTH (μm)
0
100
200
300
400
500
600
700
800
900
2.30
2.40
2.50
2.60
2.70
2.80
2.90
3.00

INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 97/01790

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 H01S3/108 G02F1/39

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 H01S G02F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 3 628 186 A (ASHKIN ARTHUR ET AL) 14 December 1971 cited in the application see column 2, line 10 - line 54 see column 2, line 74 - column 4, line 43	1-15
P,X	COLVILLE F G ET AL: "CONTINUOUS-WAVE, SINGLY RESONANT, INTRACAVITY PARAMETRIC OSCILLATOR" OPTICS LETTERS, vol. 22, no. 2, pages 75-77, XP000679184 see figure 1	1-15
A	US 5 181 211 A (BURNHAM RALPH L ET AL) 19 January 1993 see column 5, line 11 - line 32	1,2

-/--

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

2

Date of the actual completion of the international search	Date of mailing of the international search report
9 October 1997	27/10/1997

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Galanti, M

INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 97/01790

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
A	WO 94 24735 A (LIGHT AGE INC) 27 October 1994 see page 4, line 17 - page 7, line 10 ---	1,3-8
A	YANG S T ET AL: "Power and spectral characteristics of continuous-wave parametric oscillators: the doubly to singly resonant transition" JOURNAL OF THE OPTICAL SOCIETY OF AMERICA B (OPTICAL PHYSICS), SEPT. 1993, USA, vol. 10, no. 9, ISSN 0740-3224, pages 1684-1695, XP002043022 see abstract see page 1690, right-hand column, line 3 - page 1691, left-hand column, line 28 ---	1,8
A	BOSENBERG W R ET AL: "CONTINUOUS-WAVE SINGLY RESONANT OPTICAL PARAMETRIC OSCILLATOR BASED ON PERIODICALLY POLED LINBO3" OPTICS LETTERS, vol. 21, no. 10, pages 713-715, XP000589950 -----	1,8

2

INTERNATIONAL SEARCH REPORT

Information on patent family members

Inter: nal Application No
PCT/GB 97/01790

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 3628186 A	14-12-71	BE 747488 A	31-08-70
		DE 2012226 A	01-10-70
		FR 2035101 A	18-12-70
		GB 1265680 A	01-03-72
US 5181211 A	19-01-93	NONE	
WO 9424735 A	27-10-94	US 5606453 A	25-02-97
		AU 6708394 A	08-11-94